

## LCA Methodology

## Environmental Life Cycle Assessment with Support of Fuzzy-Sets

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**Abstract.** The application of the methodology Life Cycle Assessment (LCA) is time-consuming and expensive. A definite interpretation, furthermore, is not always derivable from the determined results. The reason for the leeway of interpretation is frequently due to the imprecision and uncertainty of the ingoing data. An improved clearance of interpretation is to be expected by an ecological evaluation of methodology with the support of fuzzy-sets. The influence of uncertainties of ingoing data on evaluation results becomes transparent through a representation as fuzzy-sets. Thus, the interpretation of an uncertainty of assessment results is reduced in comparison to usual procedures for environmental LCA thus far. Time and cost saving is to be expected from the fact that the extensive quantification of many energy and mass flows is replaced by a fuzzy-set supported iteration loop, with which only the exact quantification of a few important flows is necessary.

**Keywords:** Fuzzy-sets; LCA; Life Cycle Assessment; methodology

## Introduction

Life Cycle Assessment (LCA) refers to a methodology for assessing and evaluating the environmental, occupational health and resource consequences of a product through all phases of its life: extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling, and final disposal (Ong 1999). LCA examines and quantifies the mass and energy flows used and wasted, and assesses the impact of the product, the process or the activity on the environment. LCA usually facilitates the systematic collection, analysis and presentation of environmentally-related data.

The steps involved in LCA are as follows:

1. Identification of the goals and boundaries of LCA.
2. Analysis of inventory data to achieve a balance between material and energy in the system.
3. Evaluation of the system's impact on the environment.
4. Assessment of the most promising system improvements to reduce the negative environmental impact, including an interpretation of the influence of ingoing data on the total result.

The results of an LCA indicate when the selection of one product over another, or when a modification made to the system, has the desired total result of decreasing environmental impacts from all the life cycle stages. Improvement assessment supports side-by-side comparisons of alternative systems. It allows the user to choose the most environmentally-friendly product, process or activity from among comparative products.

There is still no single, correct way to perform an LCA currently. The impact assessment step (3.) and the improvement analysis (4.) are still under discussion. Impact potentials like global warming potential or ozone depletion potential are widely used in environmental life cycle assessing. Fuzzy expert systems are discussed for more site-dependent categories like acidification or eutrophication, e.g. in Thiel (1999). A more generalized approach of an estimation in the consequences of technology applications is worked out in Ludwig (1998) or in Perrone (1998). The aim of these approaches based on fuzzy logic is to forecast the most probable environmental impact including any uncertainties arising from the variables and their interactions, as well as the lack of data (Ludwig 1998). Thus, the focus is on the forecasting of environmental impact of products, processes or activities, which is to be done as good as possible. In terms of the theory of probabilities, this means that the focus is on the mean value, but not on the range of uncertainty.

The fact is that even with small uncertainties of inventory, data making an absolute decision for or against a product, process or activity is not really possible (Pohl 1996). One point of the discussion is how to manage the influence of uncertainties of inventory data on aggregated evaluation result or, in terms of probabilistic aspects, on the range of uncertainty of the result.

In Pohl (1996), proposals are discussed for the modelling of uncertainties in inventory data and impact assessment. Tools or algorithmic procedures for more transparency of uncertainties of impact categories, or of the total result where mass and energy flows are aggregated, however, are not given.

The 'Society for the Promotion of Life Cycle Assessment' (SPOLD) developed a working sheet for handling uncertainties of inventory data (Singhofen 1996). An average value

and the corresponding uncertainty of each mass and energy flow has to be filled in. The further processing of the uncertainties in impact phase remains unclear. The only given hint is that it is important to know the influence of the uncertainty on the total result. However, a clear way of interpreting the uncertainty of a highly aggregated result of an impact category like the greenhouse effect, or the even more aggregated total result, is missing.

## 1 Starting Point and Goal

In the contribution, a preventive evaluation methodology and an iteration loop with the support of fuzzy-sets are described. Fuzzy numbers are used for modelling uncertainties in a database. Data uncertainties are, for example, data sources from a different origin and quality or measurement uncertainties. The methodology includes results of impact categories as well as a total result monitored as a single value comparable, for example, to the result of the Eco-Indicator (Goedkoop 1995). Additionally, the ranges of uncertainty of the results are transparently presented as fuzzy-sets. Thus, the interpretation of the results is more user-friendly in comparison to usual procedures of LCA thus far.

The approach presented supports a user-friendly handling of LCA, especially the handling of uncertainties in inventory data. A reduction of the uncertainties in mass and energy flows is not to be expected. The methodology assumes that impact potentials and respective weighting factors are known. The approach supports the interpretation of the results and not how one can estimate the consequences of any activities on environmental impact.

In addition, an iteration loop is discussed with which one is able to filter out the big points concerning mass and energy flows and their uncertainties. It is to be expected that this methodology leads to time and cost saving when calculating an ecological indicator, since only dominant energy and mass flows must be estimated with high accuracy.

An application of the modelling of uncertainties in a database and an iteration loop for the selection of an environ-

mentally more compatible process is shown for a wave soldering process of a printed circuit board.

## 2 Preventive Evaluation Methodology and Iteration Loop with the Support of Fuzzy-Sets

### 2.1 Modelling uncertain information

With the help of the fuzzy-set theory, the classical set-theory is extended, as opposed to the classical set-theory, where it is clearly determined whether an item belongs to the set (e.g. 'one' or 'true') or not (e.g. 'zero' or 'false'). In the fuzzy-set theory, membership degrees also exist between zero and one.

For  $\mu$ , the term membership function of the fuzzy-quantity is usually used, which basically relates the membership degree  $\mu(x)$  from the interval  $[0, 1]$  to each  $x \in G$ , with  $G$  as a basic quantity (Yager 1992). Uncertain information can be modelled by membership functions, and can be illustrated graphically and linked, for example, by logical or arithmetic operations. An example is illustrated in Fig. 1.

The uncertainty of any mass or energy flow can be presented as a fuzzy-set, as statistical functions as well as intervals of estimations can be modelled as fuzzy-sets (Bandemer 1993, Chevalier 1996). A 'pessimistic' and an 'optimistic' uncertainty interval is assumed for the modelling (Pohl 1996). For the pessimistic estimation, a broad interval,  $I_{2.5}$ , is selected in order to consider a large area of possibilities.  $I_{2.5}$  means that the width of intervals are two-and-a-half times the relative standard deviation,  $s_{rel}$ , as estimated in per cent. The optimistic estimation is based on the conception that plausibility considerations and a high number of measurements can limit the area of possibilities fairly exactly, and that the interval  $I_{0.5}$  is therefore selected. In the formulas for the determination of corner points of a trapezoidal fuzzy-set in Fig. 1, these two uncertainty intervals are integrated. The difference between the right and left corner point of the trapezium are in a rough estimation in proportion to the range of uncertainty.

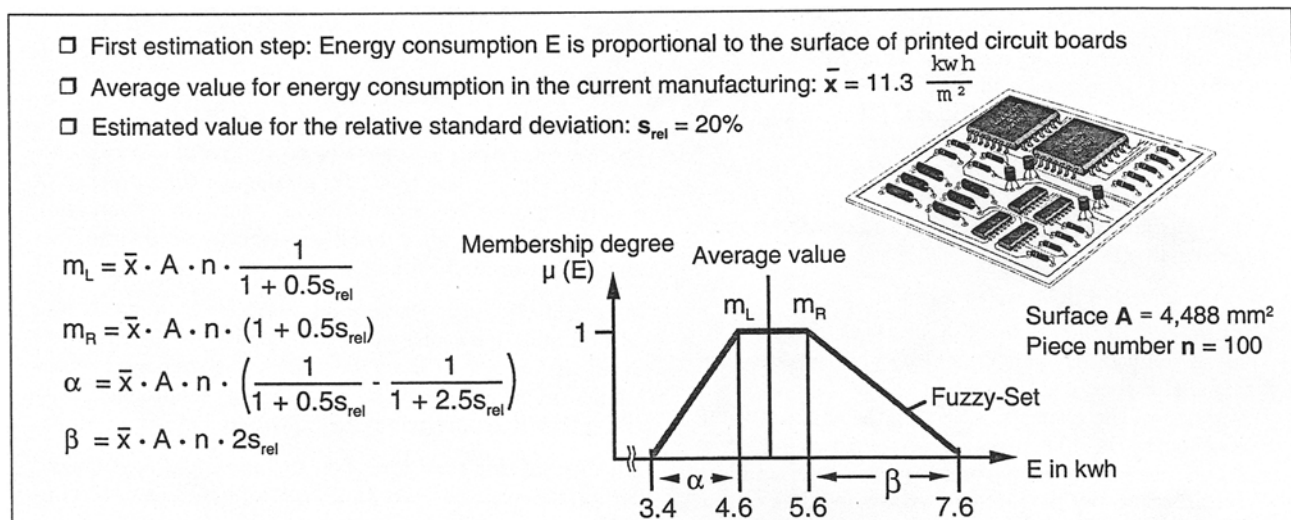


Fig. 1: Example for modelling uncertain information with fuzzy-sets (Weckenmann 1998)

## 2.2 Preventive evaluation methodology with support of fuzzy-sets

With the support of fuzzy operations, the inventory data (presented as fuzzy-sets) is classified according to the suggested impact categories, as greenhouse effect or ozone depletion (SETAC 1994). Subsequently, it is graded within the categories by partially, already internationally determined equivalence factors (e.g. 24.5-times weighting for methane compared with carbon dioxide within the impact category greenhouse effect) and aggregated by fuzzy operators to a characteristic value (characterisation). Beyond that, the results of the impact categories are graded among themselves, standardized on the basis of a comparison product and then linked by fuzzy operators. A product or a process is thus evaluated with an environmentally-related fuzzy-set or after defuzzification with only one characteristic value, 'Green Fitness' (Fig. 2). This one characteristic value does not mean that the results of the impact categories are lost. It is preferable to take a single value for comparing products and processes a first time.

The indicator 'Green Fitness' is, for example, comparable with results of the Eco-Indicator (Goedkoop 1995). Differences may appear, as the weighting factors for the impact categories do not fully correspond with one another.

The weighting factors used for the aggregation of inventory data, as well as those for the aggregation of the results of the inventory categories, are based on the principles of (SETAC 1994). They are discussed in Eyerer (1996) or Heijungs (1992), for example. To keep the model in this stage of development as simple as possible, the uncertainty of the weighting factors themselves is excluded. Suggestions for this step are made in Pohl (1995).

In contrast to the approaches of Ludwig (1998) and Thiel (1999), the scheme shown in Fig. 2 is not a rule-based one, as it is not the goal to find a new methodology for forecasting environmental impacts. Fuzzy numbers are taken for inventory data instead of for using crisp values. With these fuzzy numbers, the uncertainties of the ingoing data are modelled. An example for the modelling is given in Fig. 1. The fuzzy numbers within the inventory categories are aggregated by fuzzy multiplication. In Fig. 2, the fuzzy multiplication operation is symbolized with an  $\otimes$ , the fuzzy addition operation with a  $\oplus$ . These fuzzy multiplication and addition operations are basically discussed in the works of Dubois (1978) and Dubois (1980).

The result of a fuzzy-set is only worthy when comparing two or more products. One can clearly decide from the range of uncertainty – which is in proportion of the distance of the trapezium corner points – when a product, process or an activity is more reliable than the compared one.

A widespread field of possibilities for evaluation is put at disposal to support the analysis of a Life Cycle Assessment. The specification of a highly aggregated evaluation result as a fuzzy-set indicates both the scalar defuzzified value 'Green Fitness' and the entire uncertainty or reliability. With the value 'Green Fitness', an absolute comparison of product or process alternatives regarding the environmental compatibility is possible. The comparison of the entire uncertainty indicates if the scalar values actually permit a definite decision regarding the product or process selection.

It follows the interpretation of the results when comparing two or more products (or processes or activities): A product A is preferable if its value 'Green Fitness', which presents the total environmental impact, is less than this of product

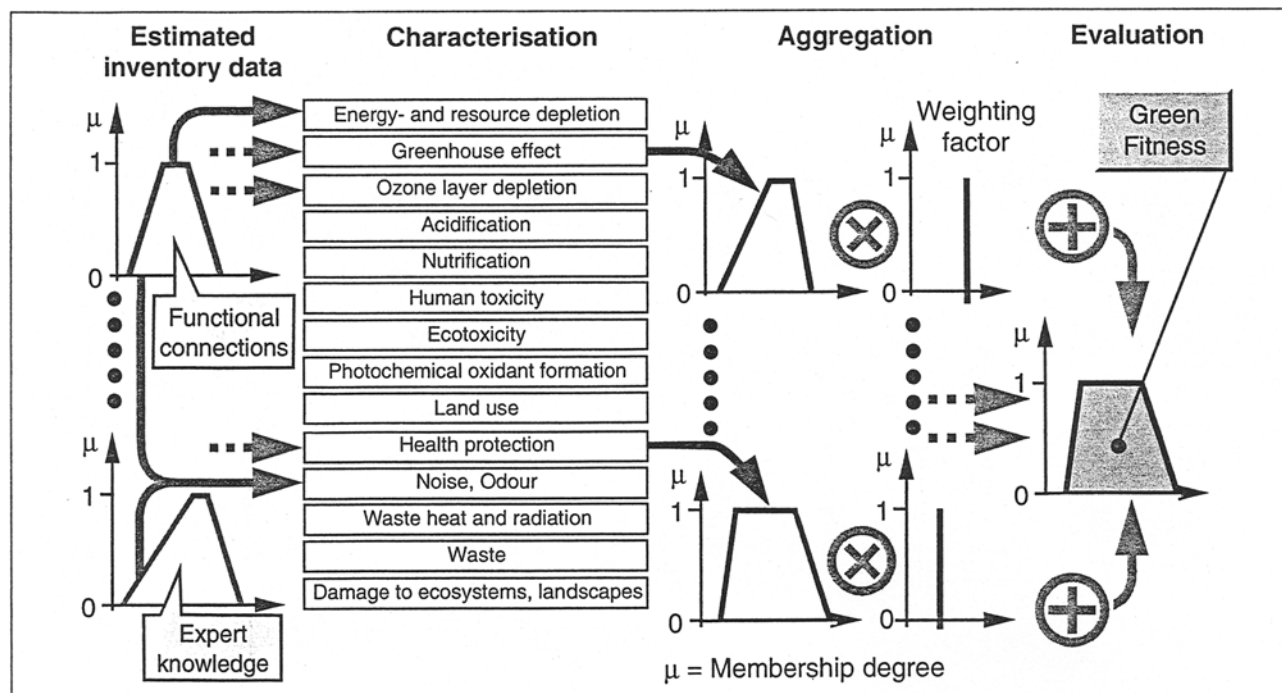


Fig. 2: Scheme for the fuzzy-set supported evaluation methodology

B. In addition, the ranges of uncertainty of both total results are not, or nearly not overlapping. With large overlapping fuzzy areas one has to decide for product A, if 'Green Fitness' is less than that of product B, plus the ranges of uncertainty are nearly identical. A definite decision, for example, is not possible if the results of the compared products or processes, presented as fuzzy-sets, overlap widely. This last case is the 'usual case', when taking rough estimations for mass and energy flows.

With assistance of a modified dominance analysis, the energy and mass flows mainly influencing the ecological characteristic value 'Green Fitness' (Fig. 2) and the reliability of the evaluation result are found out. The dominance analysis, until now applied in publications, helps to determine those mass and energy flows which have a high impact on the total result. But with the modified dominance analysis, not only the dominant mass and energy flows are found out. The dominant uncertainties are also determined. The analysis for uncertainty supports the user to determine the dominant uncertainties concerning the energy and mass flows. It helps to find out which flows are most responsible for the range of uncertainty and, in this way, is responsible for the overlapping of the fuzzy trapeziums.

### 2.3 Iteration loop with support of fuzzy-sets

An approach for time and cost saving is given with an iteration loop as follows (Fig. 3): A rough estimation of inventory data of the products is analysed, which is to be compared on its environmental friendliness. If no definite decision for or against a product is possible due to the overlap area of the resulting fuzzy-sets, then, with the help of the dominance analysis for uncertainty, those energy and mass flows are identified which dominate the uncertainty of the total result. The identified energy and mass flows are to be determined more accu-

rately in a second iteration loop. The loop is repeatedly passed through until a definite decision can be made. Cost and time-saving is to be expected by this procedure, since not all inventory data has to be known with the same accuracy. For a huge amount of ingoing data, a rough estimation is sufficient.

### 3 Example

The mode of operation of the environmental evaluation methodology and the iteration loop with support of fuzzy-sets is explained on the basis of the assessment of the wave soldering process of an exemplary printed circuit board TX and - regarding the manufacturing processes - modified versions of it. The printed circuit board TX is used in equipment of home entertainment electronics.

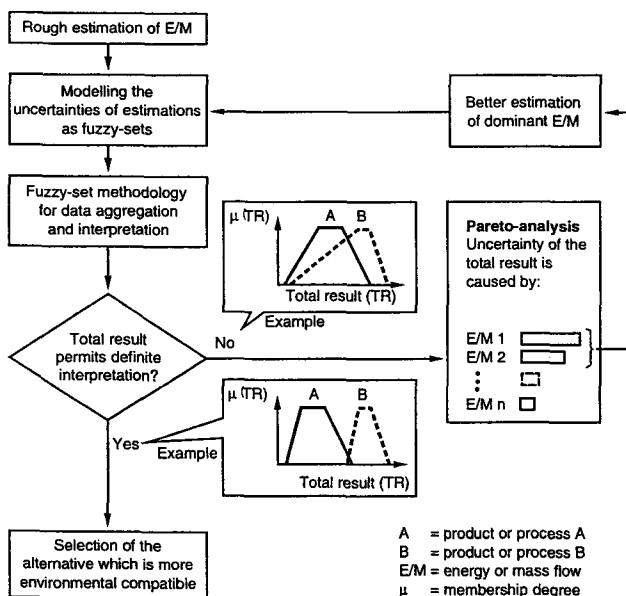
Table 1 shows increasing or decreasing energy and mass flows of the modified versions in comparison to the conventionally soldered printed circuit board TX. Hereby, it is assumed that 0.75 kWh of electricity are consumed for the production of 1 m<sup>3</sup> nitrogen. Furthermore, it is assumed that the necessary quantities of soldering bath waste and fluxing agents are reduced by the wave soldering under inert gas to 70 and 90 per cent, respectively.

**Table 1:** Measure catalogue for the increase of the eco-efficiency with the wave soldering process

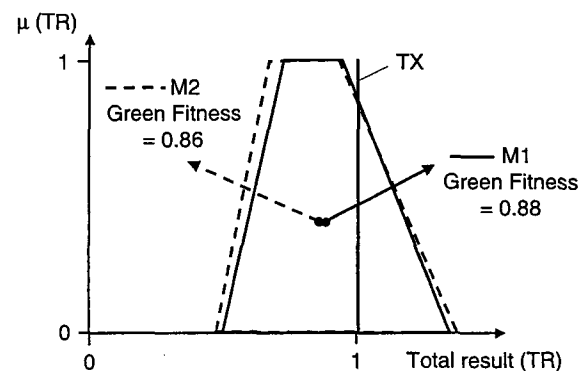
	M1 Wave soldering under inert gas	M2 Increase of thermal efficiency
Energy	+7.4%	-20%
Fluxing agents	-90%	0%
Soldering waste	-70%	0%
Nitrogen	+12m <sup>3</sup> /h	0%

The mentioned mass and energy flows lead to many more flows. The increased energy consumption means an increased output of, for example, nitrogen oxide, sulphur dioxide, and carbon dioxide. These flows influence the results of several impact categories, such as for instance, sulphur dioxide which is included in acidification potential as well as in human toxicity potential.

Fig. 4 illustrates the total result of the printed circuit board M1 and M2 in each case manufactured with modified manufacturing processes compared to the printed circuit



**Fig. 3:** Iteration loop for the selection of the environmentally more compatible product or process alternative (Weckenmann 1998)



**Fig. 4:** Comparison of M1 and M2 with support of fuzzy-sets

board TX. An improvement of the environmental compatibility is to be expected compared to the printed circuit board TX with all suggested measures. It shows that the measure 'increase of the thermal efficiency' (M 2) indicates a higher eco-efficiency compared to the measure 'soldering under inert gas' (M 1). The values for 'Green Fitness' show that measure M 1 leads to an improved eco-efficiency of 12%, M 2 to one of 14%.

In comparison to TX, M1 leads to lower impact potentials for

- Ecotoxicity, -38%,
- Photochemical oxidant formation, -78%,
- Waste, -38%.

An increase in environmental impact has to be recognised in

- Greenhouse effect, +7%,
- Human toxicity, +8%,
- Acidification, +8%,
- Nutrifaction, +7%.

The environmental impact decrease arises especially due to the reduction of soldering waste and fluxing agents.

The ranges of uncertainty of the final result of M1 and M2, however, indicate large overlaps. Therefore, a definite decision for or against M1 or M2, is not possible. The statements specified above regarding eco-efficiency on the base of the values of 'Green Fitness' must be examined in more detail. It is essential to find out the most important mass and energy flows until the final result is definite, i.e. the overlaps of the evaluation results presented as fuzzy-sets are negligibly small. The application of the modified dominance analysis for the wave soldering process, the most important flow which was detected, is shown in Fig. 5.

The total result – the value 'Green Fitness' as well as the range of uncertainty – is mainly dominated by the emergence of the nitrogen oxide resulting from the production of electrical energy. Further main influences come from sulphur dioxide and carbon dioxide, likewise resulting from the production of electrical energy. These three substances form a proportion of approx. 60 per cent of the uncertainty of the final result all together (Fig. 5). Therefore, a more exact estimation for the energy consumption is necessary. The iteration loop (Fig. 3) is activated by the identification of the important influencing factor 'energy consumption' on the uncertainty of the final result.

Concerning the second iteration loop, it is assumed that the energy needed for the measurement of M1 as well as the

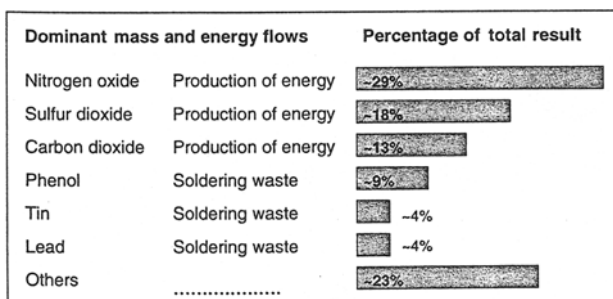


Fig. 5: Dominance Analysis

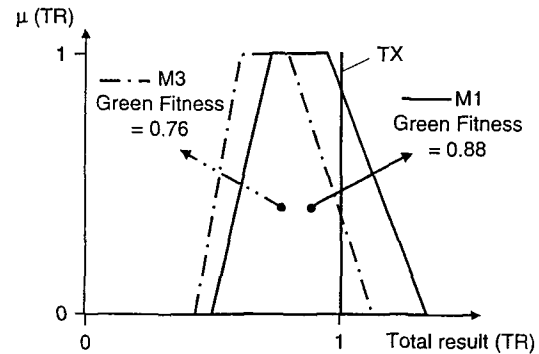


Fig. 6: Comparison of M1 and M3 with support of fuzzy-sets

estimated relative standard deviation (see Fig. 1) could be reduced to 90% (called M3). Fig. 6 shows the total result of M3 in comparison to M1.

M 3 leads to a further improvement regarding the environmental compatibility. With the measurement of M 3, the characteristic value 'Green Fitness' would be 0.76. Fig. 6 indicates that M 3 leads to a lower range of uncertainty. The fuzzy-sets do not overlap this much, other than in Fig. 4. This means one can distinguish between M1 and M3 (2. Iteration, Fig. 6) better than between M2 and M1 (1. Iteration, Fig. 4). The result indicates that the energy need is one of the 'big points' regarding the wave soldering process.

#### 4 Conclusions and Outlook

An environmental evaluation methodology and an iteration loop with support of fuzzy-sets was described. With this assistance, the analysis of the evaluation results is supported and the expenditure for Life Cycle Assessment is reduced at the same time. For the modelling of uncertain, ingoing data, fuzzy-sets are consulted. With application of the methodology for a wave soldering process, it was shown that one rough estimation is not sufficient to distinguish the environmental impact of two different process improvements even for this simple example. The demonstrated iteration loop indicated the 'big points' on the environmental impact concerning the mass and energy flows. With this knowledge, it was possible to find out the energy consumption as an efficient reduction potential.

For this evaluation methodology, a software-prototype 'Green FIT' (Fuzzy-Set supported Life Cycle Interpretation Tool for greening products and processes) was compiled. With its assistance, products and processes can already be evaluated in planning and development phases regarding their environmental compatibility and can be optimised with consideration of the certainty of the interpretation of the evaluation results. The potential effects of optimisation measures can be simulated with the help of the software and, thus, the efficiency of a measure can be evaluated.

Potential for further development is to be seen in particular with the fuzzy-set modelling of information about the quality of data. Information about the quality of data, for example, is the chronological relation of the acquisition of data. In addition, linking with an economic evaluation methodology would

be desirable. Through this linking, while at the same time determining the eco-efficiency, the costs and benefits of an ecological improvement measure could also be worked out.

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## Preventive Ecological LCA of Printing Process with 'Green FIT' Software Comparison of Three Different Printing Processes Currently Available

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Three different printing processes (cardboard-, role-, and screen-printing processes) currently available were examined with the aim of establishing the most environmentally sound printing process. Based on the data of energy and mass flows for each of the printing processes, inventory analyses are compiled.

The calculation is carried out for 2,000 pieces of etiquette and a first rough estimated relative standard deviation is assigned to each data. The role-printing process is chosen as a comparison printing process. The equivalence of three mentioned printing processes is considered by using the same functional unit and equivalent methodological considerations (e.g. data quality, system boundaries). Application of the fuzzy-set preventive evaluation methodology and the 'Green FIT' software for three printing processes enables to identify the most environmentally friendly printing process. The 'Green Fitness' of cardboard- and screen-printing processes results in 0.62 and 3.32 respectively, whereas the role printing process has a fixed value of 1.0. The Green Fit-

ness Value of 0.62 leads to an improvement of eco-efficiency of 38 per cent or causes the 62 per cent of 'environmental loads' of the role printing process. In conclusion, the cardboard-printing process is the most environmentally friendly printing process. In addition to the better Green Fitness, there are also no overlaps of the fuzzy-sets in the final result. Because of this non-overlapping, one can conclude that even in the worst case cardboard is better than the screen-printing process regarding its environmental friendliness. Or in other words: even with a rough estimation of the energy and mass flow up to 55 per cent, the result is totally clear. Green FIT Software supports the information relating to the emission which influences the ecological value 'Green Fitness' (Dominance analysis). The results of dominance analyses for printing processes were as follows: The emission is dominated by SO<sub>2</sub> sulphur dioxide, NO nitrogen oxide and NH<sub>3</sub> ammoniac, a result of the electric energy production. These three emissions make out 75 per cent (cardboard-printing process) and 65 per cent (screen-printing process) of the total emission.